Load-Deflection Tests and Computer Analyses of a High-Precision Adhesive-Bonded Antenna Reflector Panel

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New adhesive-bonded panels are being investigated as a part of an effort to extend and upgrade the 64-m to a 70-m antenna network. Load-deflection tests were conducted on a sample high-precision adhesive-bonded panel for comparison with design criteria. Two computerized structural models were developed in order to predict the deformation patterns under different types of distributed and concentrated loadings. The main purpose was to obtain empirical stiffness factors for the slit beams and girders in the panel structure. With determination and use of the empirical stiffness factors, there is a good agreement between the theoretically predicted deflections and the test measurements. It was also found that the new bonded panels satisfy the stringent design specifications and surface tolerance bounds.

I. Introduction

New high-precision adhesive-bonded panels are being investigated under the Advanced System Program's research and development effort in order to replace the traditional rivetted panels, reduce fabrication costs, and improve the surface tolerance characteristics.

The new adhesive-bonded panels, if successful, would be used in the current 64-m antenna network rehabilitation and extension project at X-band. The new panels are expected to reduce about 0.5 dB of gain loss at X-band.

II. Panel Description

The test panel is adhesive-bonded and has a solid 0.18-cm (0.070-inch) skin thickness with no skin perforations. It has circumferential beams at 35.6-cm (14-inch) centers and a radial girder at each of two sides to support the beams as shown in Fig. 1. Beams and girders are zee sections, slit and reinforced (Figs. 2 and 3). The test panel is fabricated under a JPL contract to Toronto Iron Works (TIW) of Sunnyvale, California and a subcontract to COSPAL in Bergamo, Italy.

The purpose of this test was to evaluate the response of the bonded panels for distributed loadings that are representative of environmental wind and gravity loadings, and to determine empirical stiffness and residual deflection factors due to the slitting of girders and beams.

A series of tests were conducted to measure panel deflections due to stimulated wind loadings and specified, concentrated shoe loads up to 135 kg (300 lb). The geometry of the test panels is similar to panel number 8 of the new 34-m

AZ/EL antennas, recently built by TIW for Deep Space Stations 15 and 45. In order to provide a higher structural stiffness, the new test panels were designed with ten back-up circumferential beams, instead of seven, as originally employed for the 34-m antennas.

III. Theoretical Models

Two computerized structural models were developed for simulation of the deflections of the test panel. The first model for theoretical panel deflection analysis is the FORTRAN program PANELDEFL. PANELDEFL was designed to provide analysis for the full set of panel configurations used in a complete antenna. The analysis model is automated using a minimum description of the essential geometry and construction features of each panel of the set. The PANELDEFL program provides a microwave pathlength analysis and summary for the set of all of the panels, as well as for each individual panel. The method of deflection analysis is to integrate the Euler-Bernoulli differential equations for the beams and girders. A more detailed description of the PANELDEFL program can be found in Appendix A.

The second panel structural model was developed by using the NASTRAN finite element program for the tested panel as a check. Since the PANELDEFL program does not use finite element approximations, it is expected to be more accurate than NASTRAN for the present problem. A description of the NASTRAN panel deflection model is given in Appendix B. Comparison of the outputs of the two programs showed the results to be almost identical.

The results of theoretically predicted panel deflections from PANELDEFL were compared with the measured data. This procedure has provided good validation and correlation of the computer models and good estimates of the material elastic properties.

IV. Test Loading Configurations

Five series of tests were conducted on the adhesive-bonded panel, which comprised both the distributed loading and the concentrated loading cases (Table 1). The test configurations were of two kinds:

A. Panel without center supports

B. Panel with center supports.

The test bed consists of a steel surface plate and I-beam fixture that provided rigid panel support and measurement points. The whole test bed, together with the sample panel, is shown in Fig. 4. A schematic diagram of the test panel is given in Fig. 5. A total of 19 dial indicators were used to measure the panel deflections in various locations, which are shown in Fig. 6. The test configurations are described as follows.

A. Panel Without Center Supports

The maximum distributed panel loading was 39 kg/m^2 (8.0 PSF). This distributed load for the sample panel corresponds to a uniform thickness of about 2.54 cm (1.0 inch) of sand. Up to 56 sandbags with predetermined weights were used to represent the distributed loading as shown in Figs. 7 and 8.

The girder bending stress was estimated to be only about 210 kg/cm^2 (3000 psi), which is less than one-tenth of the yield stress. After the distributed load test was completed, the concentrated load test was conducted. A concentrated load of 85.5 kg (190 lb) was used. Steel plates 30 × 30 × 2.54 cm (12 × 12 × 1 inch) were placed on top of a smaller steel plate 10 × 30 × 2.54 cm (4 × 12 × 1 inch) to simulate the concentrated shoe load as shown in Fig. 9.

B. Panel With Center Supports

Both the distributed load test and the concentrated load test were also conducted for this panel test configuration. The distributed load tests were performed first. The maximum distributed loading, with center supports in place, was about 78 kg/m (16.0 PSF) on the gross area, which corresponds to about 5.08 cm (2.0 inches) of sand.

This is a typical estimated wind load that the panel is required to support, allowing for 40% perforation area. This loading occurs when the antenna is tilted to the zenith position under a 160 km/hr (100 mph) wind. Up to 84 sandbags with predetermined weights were evenly distributed on the panel. After the distributed load test was completed, the concentrated load test was then conducted. Concentrated loads of 99, 126, and 135 kg (220, 280, and 300 lb) were used. Again, steel plates of 30 × 30 × 2.54 cm (12 × 12 × 1 inch) were placed on top of a smaller 10 × 30 × 2.54 cm (4 × 12 × 1 inch) to simulate the concentrated shoe load. Each of the 30 × 30 × 2.54 cm steel plates weigh about 18.5 kg (41 lb), while the smaller plate (10 × 30 × 2.54 cm) weighs approximately 6.3 kg (14 lb). Each load increment was intended to have a minimum of 20 minutes duration time. The recorded data reflected this time effect.

V. Comparison Between Theoretical and Test Results

Verification of the two panel structural models was made against the measured data to compare the two different

numerical approaches. Measured deflection data taken from the 19 dial indicators were recorded and compared with the theoretically predicted values.

The results are tabulated in Tables 2 and 3. Table 2 shows comparisons between the two numerical approaches for the following two cases: (1) Panel without center supports, with distributed load at 39 kg/m^2 (8 PSF); (2) Panel with center supports, with distributed load at 78 kg/m^2 (16 PSF). The results from the PANELDEFL and NASTRAN programs differed only by 3%.

Empirical stiffness factors for the panel back-up beams and girders were used to account for the slits. These stiffness factors were determined in an iterative process to achieve a good agreement with the measured deflection data. For the sample panel tested, it was found that for Girder Stiffness Factor (GSF) of 1.00 and Beam Stiffness Factor (BSF) of 0.80, the test and theory agrees to within 12%, for most of the data (Table 3). Therefore, moments of inertia for the slit beams, in the current configuration, are computed as 80% of the moments of inertia for the beams without slitting. The rivetted panels had been load-tested previously.

Comparisons of stiffness factors obtained from different tests indicated that the empirical stiffness factors are strongly dependent on the panel configurations.

Table 4 shows the comparison of empirical stiffness factors for panel girders and beams for three tests. A 3-day duration test was also conducted to study the hysteresis of the panel. A concentrated load of 135 kg (300 lb) was applied at the center of the panel and maintained for three days. Daily readings of the dial indicators were made. However, after the load was removed, no permanent deformation was observed.

VI. Summary and Conclusions

At the specified level of loads, the tested adhesive-bonded panel was found to deflect linearly with the load, for both the distributed and concentrated loading cases as shown in Figs. 10 and 11. Deflections showed insignificant hysteresis when the load is removed, even for the 3-day-long duration test. The adhesive-bonded panel withstood the specified level of wind loads, as well as the concentrated shoe load, without any apparent degradation.

The empirical stiffness factors for the slit beams and girders used in the panel structural models were found to be strongly dependent on the panel configurations. The variation of the panel configurations include whether the panel is rivetted or bonded, and whether the panel skin is solid or perforated. The spacing of beams and the overall geometry of the panel also influence the determination of the empirical stiffness factors. Because of such a wide variation of the panel configurations, and because there is no simple theoretical way to compute or predict the stiffness factors, it is concluded that a test is needed for each type of panel configuration in an antenna set.

Acknowledgments

Table 1. Panel load-deflection tests

Test series	Center supports	Loading type	Load level
1	No	Distributed	19.5 kg/m^2 (4 PSF); 39 kg/m^2 (8 PSF)
2	Yes	Distributed	39 kg/m^2 (8 PSF); 78 kg/m^2 (16 PSF)
3	Yes	Concentrated	99 kg (220 lb); 135 kg (300 lb)
4	Yes	Concentrated	126 kg (280 lb)
5	No	Concentrated	85.5 kg (190 lb)

Table 2. Comparison of theoretically predicted deflections (Unit: cm (inch), distributed loading)

(a) Panel Without Center Supports, at 39 kg/m^2 (8 PSF)

Theory \ Dial Indicator Number	8	9	10	16	17	21
NASTRAN Model (A)	0.106 (0.0419)	0.102 (0.0404)	0.092 (0.0362)	0.076 (0.0297)	0.096 (0.0379)	0.066 (0.0264)
PANELDEFL Model (B)	0.104 (0.0410)	0.100 (0.0395)	0.089 (0.0352)	0.075 (0.0294)	0.095 (0.0372)	0.065 (0.0259)
Ratio A/B	1.02	1.02	1.03	1.01	1.01	1.01

(b) Panel With Center Supports, at 78 kg/m^2 (16 PSF)

Theory \ Dial Indicator Number	8	9	10	16	17	21
NASTRAN Model (A)	0.0625 (0.0246)	0.0544 (0.0214)	0.0318 (0.0125)	0.0706 (0.0278)	0.0653 (0.0257)	0.0564 (0.0222)
PANELDEFL Model (B)	0.0605 (0.0238)	0.0526 (0.0207)	0.0307 (0.0121)	0.0683 (0.0269)	0.0638 (0.0251)	0.0577 (0.0227)
Ratio A/B	1.03	1.03	1.03	1.03	1.02	0.98

Table 3. Comparison of theory and test data (unit: cm)

(a) Panel Without Center Supports, Distributed Load at 39 kg/m² (8 PSF)

Deflection — Dial Indicator Number	6	7	8	16	17	20	18	21
Test (A)	0.086	0.099	0.104	0.074	0.104	0.094	0.089	0.061
Theory (B)	0.086	0.097	0.099	0.074	0.092	0.099	0.086	0.064
Ratio A/B	1.00	1.02	1.05	1.00	1.13	0.95	1.03	0.95

(b) Panel With Center Supports, Distributed Load at 78 kg/m² (16 PSF)

Deflection — Dial Indicator Number	6	7	8	16	17	20	18	21
Test (A)	0.038	0.056	0.061	0.038	0.076	0.066	0.074	0.058
Theory (B)	0.030	0.053	0.061	0.043	0.064	0.061	0.061	0.056
Ratio A/B	1.27	1.06	1.00	0.88	1.19	1.08	1.21	1.03

Table 4. Effective stiffness factor for girders and beams

Test	(7/84, Panel Numbers 3 and 9) Goldstone test on rivetted panel			(10/84, Modif. Panel Number 8) COSPAL test on bonded panel		(4/85, Modif. Panel Number 8) Goldstone test on bonded panel	
Center support	No	No	Yes	No	No	No	Yes
Panel skin	Solid	Perf.	Perf.	Solid	Solid	Solid	Solid
No. of beams				10	7	10	10
GFACT[a]	0.60	0.50	0.48	0.87	0.74	1.00	1.00
BFACT[b]	0.75	0.75	0.68	0.90	0.95	0.80	0.80

[a]GFACT = Effective stiffness factor for girders.
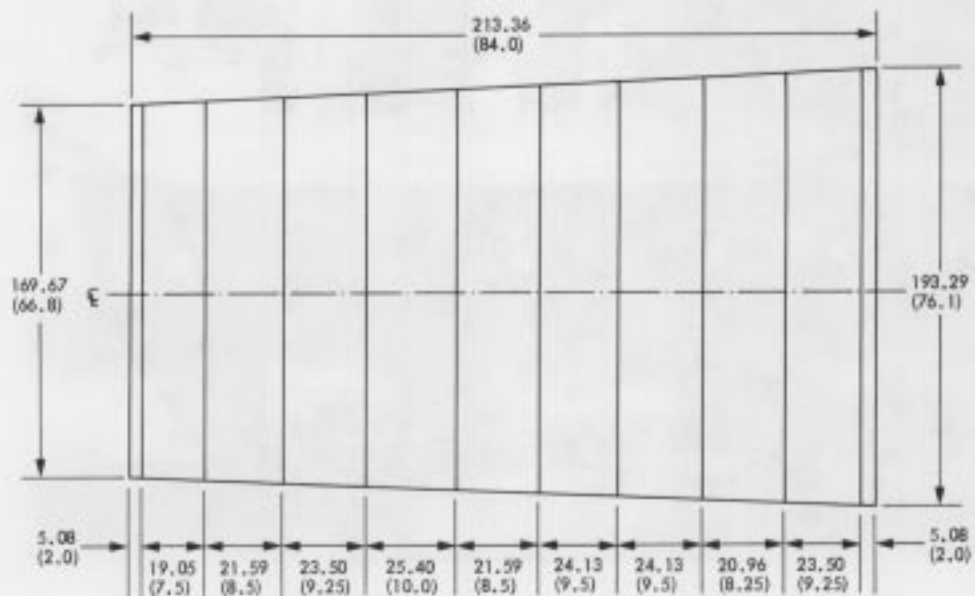[b]BFACT = Effective stiffness factor for beams.

Fig. 1. Panel dimensions and back-up beam spacings [unit in cm (inch)]
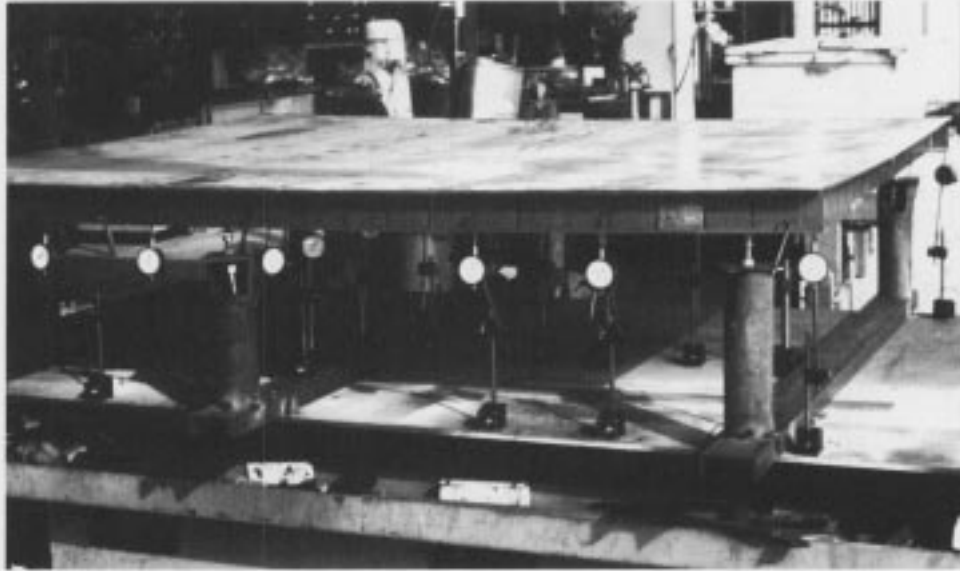

Fig. 2. Test panel showing slit girder

Fig. 3. Test panel with slit beams and girders

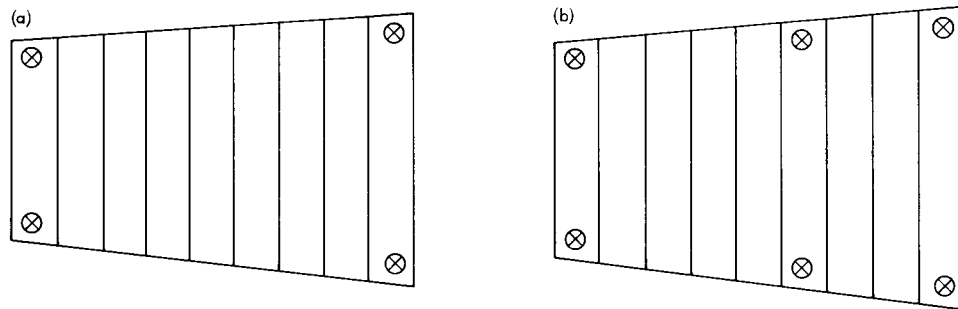Fig. 4. Sample panel with dial indicators

Fig. 5. Panel loading configurations: (a) without center supports; (b) with center supports
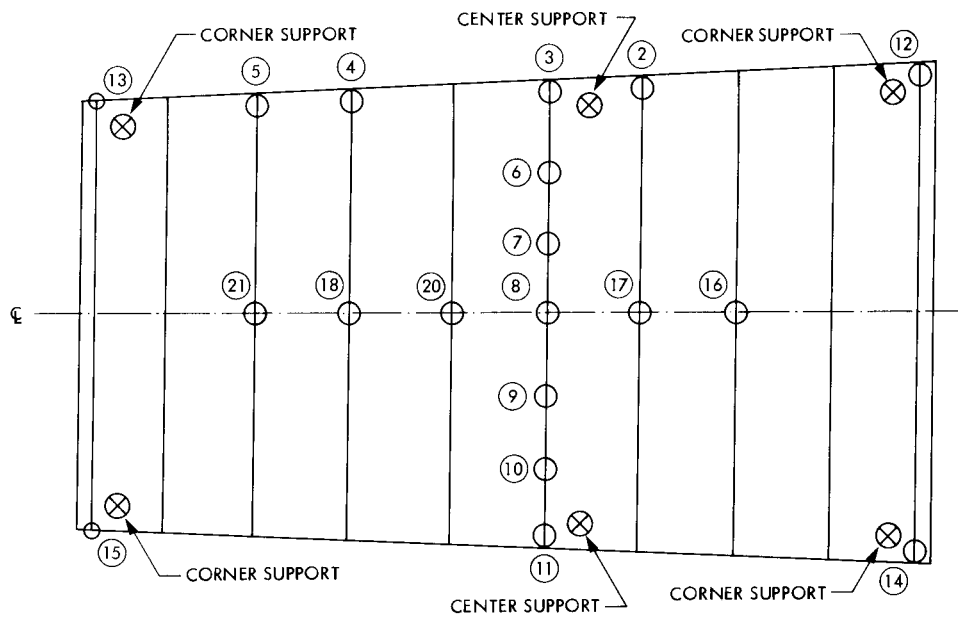

Fig. 6. Locations of the dial indicators

Fig. 7. Distributed load test using sandbags

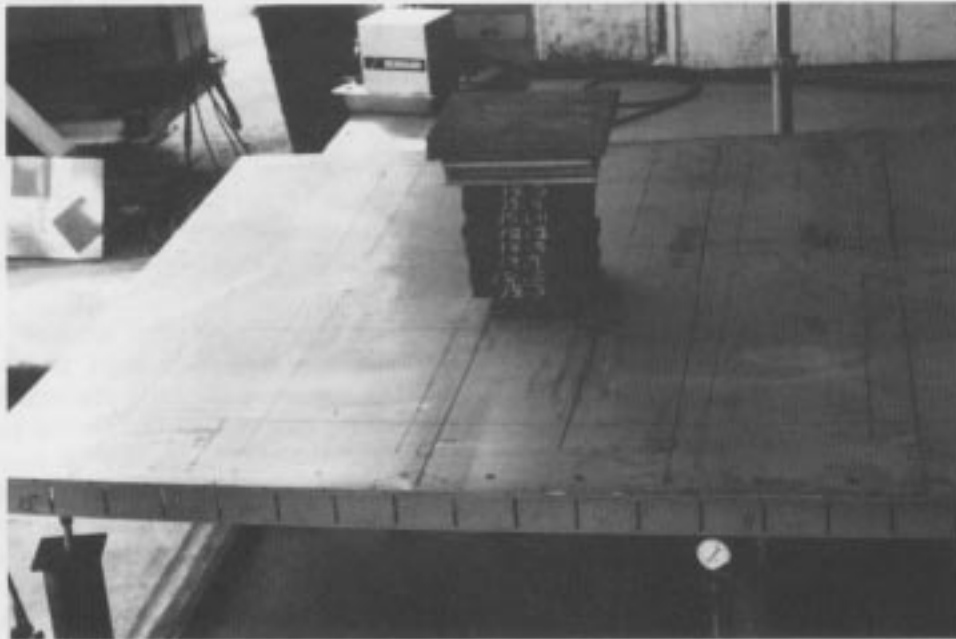Fig. 8. Up to 84 sandbags were used to represent the distributed load

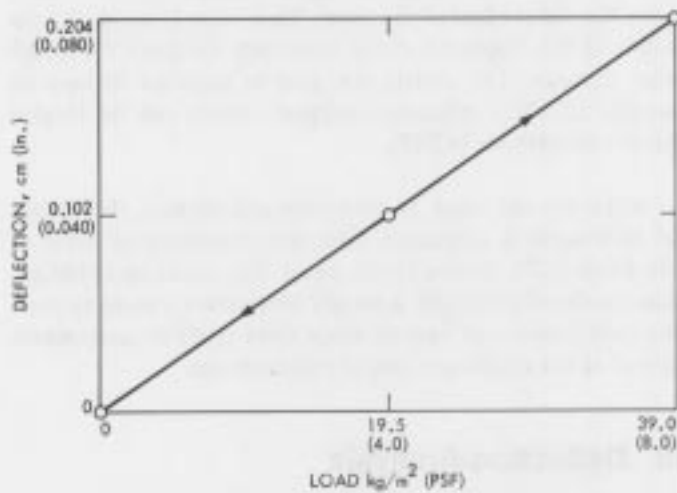**Fig. 9. Steel plates were placed on top of the panel to simulate the concentrated load**

Fig. 10. Panel deflection at dial indicator number 8 as a function of the distributed load (panel without center supports)
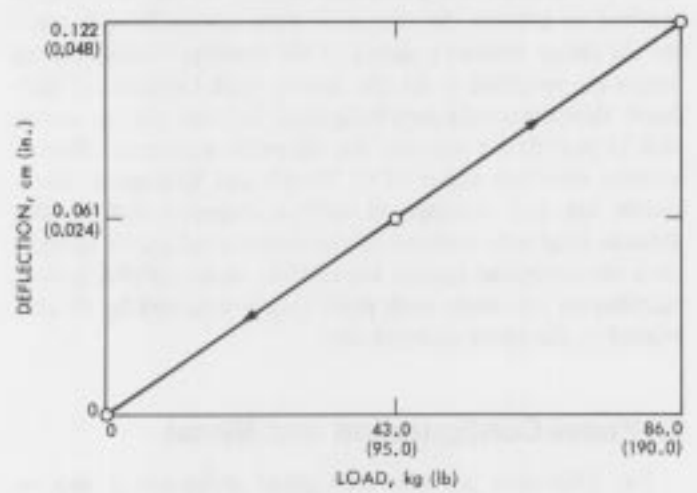

Fig. 11. Panel deflection at dial indicator number 17 as a function of the concentrated load (panel without center supports)

Appendix A

Computer Program for Panel Deflection Analysis (PANELDEFL)

I. Program Function

This computer program determines the deflections for one or a number of paraboloidal microwave antenna-reflector surface panels. In addition to performing the deflection analysis, each panel is best fit to minimize the mean square deflection errors from its ideal surface. Three fitting parameters are determined by a least squares analysis. These parameters consist of a shift in the coordinate normal to the plane that approximates the panel surface, and the two independent rotations about the panel's X- and Y-coordinate axes, which are as shown on Fig. A-1. Independently best-fitting individual panels is not always a valid procedure, so that the mean, the root-mean square (rms), and the standard deviation of the panel errors are supplied both with and without the fit. These are furnished both for the direction approximately normal to the panels' surface and also for the microwave pathlength direction. Weighting factors are applied to the analysis to approximate the area associated with each point of deflection calculation.

A comprehensive analysis of the entire set of antenna panels can be obtained by modelling one panel from each of the annular rings of panels that form the antenna surface. When this is done, the deflection analysis for each ring is synthesized to provide the rms microwave half-pathlength error for the entire antenna's panels. If the external loadings on the panels are specified to be the gravity load (weights) of each panel, then the synthesized deflections for each ring are assembled to provide the rms error for the entire surface at different antenna elevation angles of 0, 30, 60, and 90 degrees. These results are also recomputed with a common shift in the antenna focal axis direction of the entire set of panels to minimize the assembled surface error. When entire antenna surface calculations are made, each panel ring is weighted by its area relative to the entire aperture area.

II. Panel Configuration and Model

For deflection analysis each panel comprises a pair or radial girders that support a number (NRING)[1] of approximately circumferential (actually chordal) beams as shown in Fig. A-1. A number (NRIB) of equally spaced points along the axis of each beam can be specified at which deflection

[1]Capitalized terms within parenthesis are FORTRAN namelist input parameters supplied by the user. See the definitions following the $INPUT in the user instruction section.

calculations will be made. The first and the last of these points will actually fall on the girders. A trapezoidal configuration for each panel is determined by the inner (RI) and outer (RO) radii of the panel location within the antenna and by the central angle (TH). For RF pathlength analysis, it is necessary to specify the focal length (F) of the paraboloidal surface, or an approximating focal length of a quasi-paraboloidal surface.

Elastic properties of the structure are determined by specifying the bending moment of inertia of the girders (GIRDI) and beams (BEAMI), the modulus of elasticity (E) and bending efficiency factors for the girders (GFACT) and beams (BFACT). These factors are usually less than unity because of the effects of slitting the girders and beams in the fabrication process or because of other effects, such as web shear deflections. The factors are best determined by test. They conceivably could be greater than unity because of integral combining action of the surface skin sheet with the girder and beam cross sections. The surface skin is assumed to be parasitic and not to contribute to the strength of the panel.

The typical panel is assumed to be supported at two points on each girder at a distance (ENDG) in from the end of the panel. The axes of the girders are inward a distance (ENDB) from the radial edges of the panel. Thus, each beam span is the width of the trapezoid at the beam axis less twice the girder edge distance. The girders can also be specified to have an interior (ICENT) redundant support, which can be located by several methods (RINT).

Although not used in deflection calculations, the weight of each panel is computed from the cross-sectional areas of the beam (AB), girders (AG), panel skin thickness (THICK), and the density (DENS). A weight breakdown is given to show the contributions of each of these three types of components as well as the weight per unit of planform area.

III. Deflection Analysis

The loading for deflection analysis is a uniform surface load (PSF) to simulate either a wind pressure loading or a gravity loading. If the gravity loading is not known a priori, it is reasonable to run all the other data through the program just for the purpose of obtaining panel weight to establish the gravity loading.

The deflection analysis is made for beams and girders by integrating the usual differential equation that equates the

bending moment to the second derivative of displacement with respect to the longitudinal coordinate. The axes of beams and girders are assumed to be straight and contained in the secant plane. The secant plane is the plane that contains all four corner (or near-corner) girder supports. The deflections are computed normal to this plane. The loads on the beams are the distributed line loads determined from the surface loading and the beam spacing and are applied normal to the secant plane. The girder loads are concentrated reactions of the beams. The case of the redundant interior girder support is solved by the method of consistent displacements; the girder deflection is determined for a unit load at the redundant support and the unit load is scaled and applied to annihilate the girder deflection that is computed from the beam reactions when ignoring the interior support.

User Instructions

Runstream for JPL UNIVAC 1100/80 E computer:

@XQT   52219*RIL.PANELDEFL/MAP.

$$INPUT One set of namelist data per representative panel for a maximum of 24 rings.

$$END
.
.
.
.
.

$$INPUT Last panel.

$$END

@EOF

The NAMELIST input data are supplied for each panel ring as follows (see Fig. A-1 for sketch showing geometric variables):

F	Focal length of parent parabola.
RI	Inner radius of the panel ring projected on the aperture plane.
RO	Outer radius of the panel ring projected as above.
NRING	Number of rings within each panel. This is also the number of circumferential beams, including the beams at RO and RI. Maximum = 30.
NRIB	Number of radial lines within the panel. This sets the number of points on each ring beam for deflection calculations. The first and last lines are on the panel radial edge girders. Maximum = 30.

TH	Central angle of each panel in the ring, degrees.
AB	Cross-sectional area of the beams.
AG	Cross-sectional area of the girders.
GIRDI	The bending moment of inertia of the girders.
BEAMI	The bending moment of inertia of the beams.
GFACT	Effective stiffness factor for girders. Default = 0.75.
BFACT	Effective stiffness factor for beams. Default = 0.75.
ICENT	If not zero the girder has an interior support in addition to the end supports.
RINT	Distance to the interior girder support (for ICENT not zero).
	If RINT = 0.0: Support will be at the girder's center.
	If RINT = positive: It is the radial distance from the center of the antenna, measured perpendicular to the focal axis (same coordinate system as for RO, RI).
	If RINT = negative: It is the slope distance along the girder starting from RI.
DENS	Material density.
E	Young's Modulus.
PSF	Superimposed loading normal to the surface of the panel in pounds per square foot. This is the only loading for which deflection analysis is made and this could be different for each panel ring.
THICK	Average thickness of panel skins (allow for perforation) used for weight calculations.
SLOPE	The secant slope of the panel in the parent parabola. This is computed and echoed by the program. The loading is applied normal to this slope.
IBUG	0 = minimum printout. 3 = maximum printout.
ENDG	Distance from the end of the girder to the corner support point.
ENDB	Distance from the center line of the girder to the side edge of the panel.
$$END	

NOTES:

1. The minimum printout consists of the deflection matrix of the panel, panel weight, and summary rms analysis for each panel. For rms analysis, interior points are weighted by unity, edge points by one-half, and edge corner points by one-quarter.

2. Although the panel weight (beams plus girders plus skin) is computed, deflection analysis is made only for the uniform loads defined by PSF.

3. The load for deflection analysis is applied normal to the approximating plane of the panel skin. If PSF is made equal to the gravity weight of the panel then the associated deflections can be considered as the built-in bias at manufacturing. At specific antenna elevations ($0°$, $30°$, $60°$ and $90°$) the composite pathlength error is computed for all panel rings

and for the variable spring-back deflection for each of the panels in a full $360°$ panel ring. For the composite analysis of the entire surface each antenna ring is weighted by its area.

4. A best fit rms pathlength analysis is also determined for the composite antenna on the basis of a shift in the antenna Z (axial) coordinate.

5. The girder effective stiffness is computed as GFACT* GIRDI*E. Similarly the beam stiffness is BFACT*BEAMI*E.

6. Unless noted above, units are customary English inches and pounds.

7. The namelist data for successive panels does not need to repeat any information for prior panels that continue to be applicable.
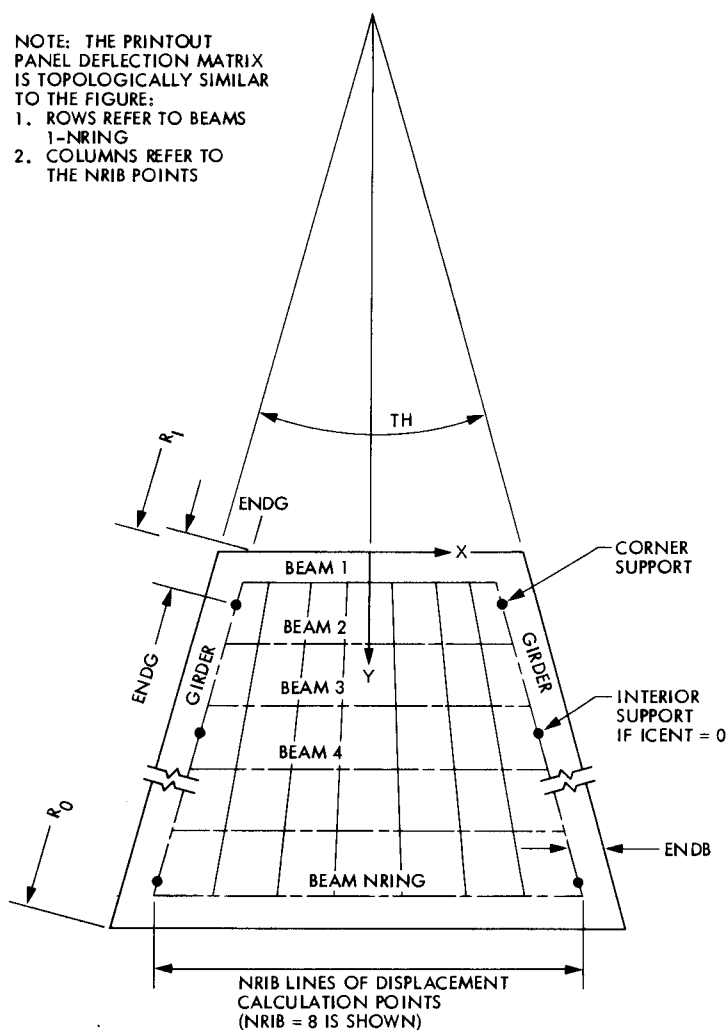

NOTE: THE PRINTOUT
PANEL DEFLECTION MATRIX
IS TOPOLOGICALLY SIMILAR
TO THE FIGURE:
1. ROWS REFER TO BEAMS
   1-NRING
2. COLUMNS REFER TO
   THE NRIB POINTS

Fig. A-1. Panel configuration

Appendix B

Panel Structural Model by NASTRAN Program

A panel structural model was developed by using the NASTRAN (NASA Structural Analysis) finite element program for the tested panel.

The essential input data and procedure are summarized in Fig. B-1.

EXECUTIVE CONTROL DECK

APPLICATION DISPLACEMENT
SOLUTION 1 (STATIC ANALYSIS)

CASE CONTROL DECK

SELECT OUTPUT POINTS DESIRED, SPECIFY
LOADINGS AND CONSTRAINTS, REQUEST
DISPLACEMENT, FORCE AND STRESS AS
OUTPUTS

BULK DATA INPUT

GEOMETRY OF TEST PANEL, PROPERTIES OF
BACK-UP GIRDERS AND BEAMS, MATERIAL
ELASTIC MODULUS AND POISSON RATIO,
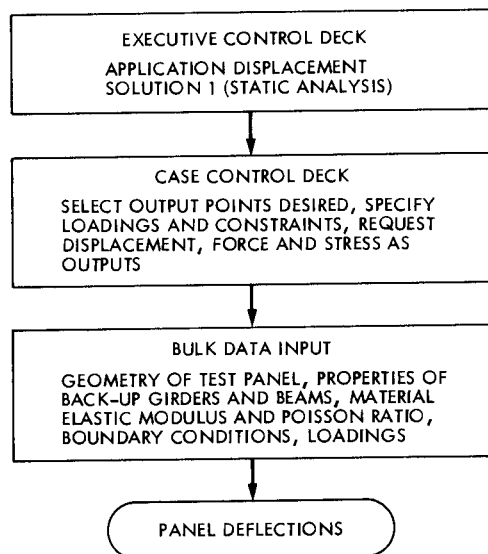BOUNDARY CONDITIONS, LOADINGS

PANEL DEFLECTIONS

**Fig. B-1. Flowchart of the essential input data
and procedure**